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"NOCTURNAL LOW LEVEL JET INFLUENCES ON MESOSCALE CONVECTIVE COMPLEX (MCC) DEVELOPMENT"

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ABSTRACT

The intent of this paper is to define what Mesoscale Convective Complexes (MCC) are and discuss their 3-Dimentional structure (Sections I & II). In section III the structure and origin of the Great Plains Nocturnal Low Level Jet will be discussed. How this nocturnal low level jet interacts with MCC's will also be addressed (Section IV). Finally, a summary of the main points will be provided along with several ideas for future areas of study. The goal is to summarize as completely as possible the current state of understanding of MCC's and their interactions with low level jets.

I. Introduction & Definitions

One of the most poorly understood yet meteorologically significant events to effect the Central Plains States of North America is the Mesoscale Convective Complex (MCC). They originate in the area of North America bounded by the Rocky Mountains to the west and the Mississippi River to the east. Occurring during the late spring and early summer months, MCC's are

responsible for a majority of the growing season rainfall for the American corn and wheat belt (Ray, 1986). Unfortunately, along with the beneficial rainfall, MCC's may also produce very intense local rainfall (causing flash flooding) and severe thunderstorms (possibly containing tornadoes, hail, high winds and intense lightening events). While these systems are significant by themselves, they are only one of a number of phenomena known as Mesoscale Convective Systems (MCS's). Therefore, an explicit set of parameters needed to be established in order to separate MCC's from the other types of MCS's.

Maddox (1980) defined the criteria to be used in the classification of MCC's. These criteria are listed in Table 1:

TABLE 1	Physical Characteristics
Size	A - Cloud shield with continuously low IR temperatures <= -32 degrees C must have an area >= 100,000 square kms
	B - Interior cold cloud region with temperature<= - 52 degrees C must have an area >= 50,000 square kms
Initiation	Size definitions A and B are first satisfied
Duration	Size definitions A and B must be met for a period >= 6 hours
Maximum Extent	Contiguous cold cloud shield (IR temperature <= -32 deg C) reaches maximum size
Shape	Eccentricity (minor axis/major axis) >= 0.7 at time of maximum extent
Terminate	Size definitions A and B no longer satisfied

From these criteria it is evident that MCC's present a very cold, nearly circular cloud shield, as viewed in the IR from enhanced IR satellites. In their mature stage, they are very easy to spot on satellite imagery and present a very ominous appearance (**FIG 1**). Small & Augustine (1992) referred to the works of Newton (1950), Fujita (1955) and Pedgley (1962) in their statement that the satellite signature of an MCC is a result of a long recognized property of thunderstorms, their ability to multiply and organize into mesoscale systems. This propensity to multiply and organize into mesoscale systems is based on the presence of three distinct atmospheric features; 1) upper atmospheric support (300mb level and above), 2) a combination of low level and middle level instabilities and 3) a low level moisture source. In section II, a discussion of the role of each of these

three features will occur while section III will illustrate how they work together to create and sustain an MCC.

II. Component Discussion

A) *Upper Level Support*: Numerous synoptic studies have been performed on MCC's in order to aid forecasters in predicting their occurrence. From these studies, several distinct characteristics have been identified as contributors to MCC development. One of these characteristics is the presence of an upper level trough to the west of the Rocky Mountains at the 200mb level (Trier & Parsons, 1993). This provides an upper level diffluent area east of the Rockies out over the Great Plains (**FIG 2**). This sets the stage for upper level mass divergence over the area of possible MCC development which acts to establish a favorable upper level environment should MCC development occur later. Another upper level feature that contributes to a favorable MCC environment in the upper levels is a 200mb or 300mb jet streak whose exit region extends over the Great Plains (**FIG 3**). The secondary circulation associated with the exit region can enhance the low level moisture flux northward from the Gulf of Mexico (the effects of this low level northward flow will be discussed fully later in this section). Thus, the presence of an upper level trough west of the Rockies and a jet streak over the Rockies provides one element for MCC development, upper level support.

B) *Middle Level Instability*: With the upper level pattern specified, attention should now focus on the middle level (500mb) synoptic situation. It is at this level that instability factors become significant for the initial development of an MCC. To start, a trough just west of the Rockies needs to be present as in the upper level situation. This provides an additional area of diffluence out over the Great Plains. However, the long wave trough at this level is not as important as the presence of some strong, rapidly moving short wave troughs moving out of the long wave trough towards the Great Plains (**FIG 4a,b,c**). These 500mb short waves may not be strong enough to be reflected in the surface pressure or temperature fields, but their presence is vital for MCC development. On the synoptic scale, there is not enough energy for strong upward vertical motion over the Great Plains. However, at the

mesoscale, these 500mb short waves provide enough upward vertical motion ahead of them for cumulus convection to develop over a wide area. Once the MCC establishes itself, the positive (warm) thermal anomaly at 500mb actually helps to intensify the short wave trough, thus allowing for the effects of the MCC to be felt downstream several days after the MCC dissipates (Ray, 1986). Thus, the MCC acts as a two way partner with the short wave trough at 500mb. First it takes energy from the short wave to allow for the initiation and growth of the MCC. Then once mature, the MCC acts to influence its environment by intensifying the short wave trough which then continues to propagate downstream with the ambient 500mb flow. Therefore, MCC's possess an ability to affect both their local weather as well as the downstream weather patterns for several days (Ray, 1986).

C) *Low Level Instabilities*: Having discussed the 500mb and above environment favorable for MCC initiation and growth, it is time to concentrate on the most complex region of an MCC, the low level (850mb to the surface). It is in these lower levels that the initial destabilization of the airmass occurs. Only after the lower levels become sufficiently unstable do the effects of the middle and upper level instability sources come into play. There are two methods that appear to create the low level instability necessary, both of which occur in conjunction with a low level southerly jet between the surface and 850mb.

The first method is present in a large number of MCC evaluations and is associated with the presence of a quasi-stationary or very shallow and slow moving cold front (**FIG 5a,b**). The frontal orientation is East - West and tends to be positioned several hundred km south of the area of future MCC development. In this instance, the MCC occurs in the initially cooler, more stable air in place after frontal passage. While initially this location tends to repress any convective development, a combination of events act to destabilize this airmass over time. Sensible heating from below, combined with the low level moisture flux from the south and the associated positive vertical velocities experienced by the low level jet north of the surface frontal boundary (**FIG 6**) destabilize the initially stable airmass (Trier & Parsons, 1993).

A second method, observed less frequently but still a significant source of instability, is associated with the mass convergence present at the leading edge of the southerly low level jet (Nicolini et al, 1993). In this instance, MCC's may develop in a region with no surface frontal boundary or well in advance of a surface cold front (**FIG 7**). This type of development may occur as an initially stable or slightly unstable airmass gets destabilized due to these low level processes. First, sensible heating from below can act to destabilize the airmass. Second, the moisture and temperature advection of the southerly low level jet flow acts to moisten and destabilize the lower layers. Finally, as the wind speeds of the low level southerly flow begin to decelerate at its northern most edge, an area of significant mass convergence develops. As the low level flow begins to intensify into the night, this low level mass convergence increases and produces a large area of positive vertical velocities. According to Blackadar (1957), "the nocturnal increase in this wind maxima is the result of an inertial oscillation of the ageostrophic wind vector as the air near the top of the friction layer is decoupled from the air below by the formation of a nocturnal inversion" (Bonner, 1968). It is at this point that convective elements gain the low level dynamic support necessary for development. Having now referenced it several times as well as identifying its important role in low level instability development, a more thorough examination of the Great Plains Low Level Jet needs to be made.

D) *Great Plains Low Level Jet*: In both cases of low level instability development, a low level southerly flow was the driving force. This low level, warm, moist southerly flow is known as the Great Plains Low Level Jet. This jet of air provides a significant source of warm humid air from the Gulf of Mexico northward through Texas into the North American Great Plains states. This flow tends to concentrate into a fairly shallow and horizontally narrow band due to both dynamical and geographical effects. According to McCorcles (1988), the Great Plains Low Level Jet can be characterized as:

1) A spring or summer phenomena,
2) located within 1 KM of the ground,
3) found in a south to southwest ambient flow,
4) favored just upwind of convection and

5) a transporter of significant amounts of water vapor.

While low level jets are not confined to the North American Great Plains, future discussion within this paper will be confined to this area.

Typically, the Great Plains Low Level Jet is most intense in the spring and summer months as a monsoonal type circulation establishes itself over the North American Gulf Coast (Bonner, 1968). This strengthening of the low level jet in spring and summer coincides exactly with the seasonal increase of MCC development. Together with this monsoonal type circulation, both upper level jet streaks and the subtropical high tend to influence the strength and position of the low level jet.

Associated with the exit region of an upper level jet streak (assuming quasi-geostrophy) is an induced secondary circulation which tends to strengthen the low level wind flow from an area of divergence to an area of convergence. At the jet streak level, the area of divergence north of the jet axis provides a mass source to the area of convergence south of the jet axis (**FIG 8**). A sinking motion is established beneath the upper level convergence area leading to a mass build up at the surface. In order for mass continuity to be conserved, a divergent flow from south to north at the surface is established which feeds mass for the upward flow beneath the upper level divergent area (Ray, 1986). This circulation will act to enhance the low level southerly flow.

Another method for enhancing the low level jet is through movement of a large scale circulation feature, specifically the Bermuda High. As the seasons move from winter towards summer, the Subtropical High begins to dominate the synoptic pattern over the Eastern U.S. during its intensification. As its influence (and associated anticyclonic circulation) moves westward over the Southern U.S., it tends to increase the southerly flow around its western edge (**FIG 9**). While this sets up a general flow of Gulf moisture into the Central U.S., the lack of any significant terrain features keeps it as a very wide band flow rather than a narrow intense stream. However, when the Bermuda High is very intense and encroaches westward into

Louisiana and Eastern Texas, its southerly flow begins to get forced up against the Central Texas Plateau. This area of rapidly rising geography acts to concentrate and deflect the southerly flow into a more narrow and intense current (**FIG 10**). As this happens, the low level jet intensifies and increases its effect on moisture and heat flux into Texas and the Great Plains states (Nicolini et al, 1993).

While any one of these factors can contribute to the moisture and temperature flux northward from the Gulf of Mexico, a combination of any of them can dramatically increase this northward flow. More directly related to MCC development however is the observed diurnal variation of the low level jet in both speed and direction. This diurnal variation coincides very well with the nocturnal nature of MCC's. As observed by McCorcle (1988) **(FIG 11a,b,c)**, there is a pronounced nocturnal increase in low level jet occurrence and intensity. This increase begins around sunset and increases to its maximum value at around 0200 local time. Having now defined and described all the major contributors to MCC development, its time to discuss how they all work together in an MCC.

III. Composite Analysis

The three key components described in Section II (upper level support, middle and low level instabilities and a low level moisture source) need to come together in just the right sequence for MCC development to occur. It turns out that the destabilization of the airmass provides the initial positive vertical velocity that sets the sequence of events in motion. This destabilization occurs due to low level warm / moist advection, not because of low level vorticity advection as has been proposed in the past (Ray, 1986). Once this initial upward motion comes in phase with the other components, the environment becomes ripe for MCC development. A description of how the low level jet interacts throughout the life cycle of an MCC follows.

The whole sequence tends to begin roughly 24 - 36 hours prior to MCC development. At this time, an upper level long wave trough (500mb and above)

establishes itself west of the Rocky Mountains, bringing a southwest flow and an area of upper level diffluence downstream of the trough axis over the Central Great Plains states. This pattern will persist in this area and become a focal point for 500mb short wave troughs to move through. Several of these short wave troughs may move through the upper level long wave trough out over the Great Plains, aiding in the development of cloud cover or precipitation depending on the stability of the airmass its moving over. However, in order for MCC development to occur, it appears that the key at 500mb is for a short wave trough to be moving out of the long wave trough axis roughly 8 - 10 hours prior to MCC development. Since MCC's are nocturnal events which tend to initiate between 2100 local time and 0000 local time, that puts the short wave trough moving out of the long wave trough around 1100 local time (Trier & Parsons, 1993). At this point, the only indication of possible future MCC development are upper level charts and surface frontal positions (**FIG 12**). The weather in the area of later MCC occurrence can range from clear and calm to variably cloudy with isolated showers or thunderstorms (depending on airmass stability). Upon identification of the upper level trough and 500mb short wave pattern, attention needs to focus on identifying any synoptic indications of nocturnal low level jet flow which could destabilize the airmass further.

As discussed in Section II, these synoptic indicators of nocturnal low level jet intensification are 1) exit region of an upper level jet streak and 2) western extent of the Bermuda High. The movement of an upper level jet streak into the upper level trough and / or the westward movement of the Bermuda High establishes a very favorable environment for low level southerly flow intensification. As the daytime heating effects weaken and the low level nocturnal inversion begins to form, the confinement of the low level jet into a small area occurs. This low level jet intensification and the associated heat and moisture flux increase occur roughly 4 - 8 hours prior to MCC development (again depending on initial airmass stability). At this point it is mid-afternoon over the Great Plains and if all the above processes are in place, the stage is set for the nights activity (Trier & Parsons, 1993).

As evening approaches, the low level processes necessary for airmass destabilization commence. The southerly winds out of the Gulf of Mexico begin to increase, pumping huge amounts of heat and moisture into the Central U.S. As this river of air moves northward, positive upward motion is initiated (either frontal related or convergence related) and the increasingly unstable airmass begins to develop convective activity. At this time (around sunset), the 500mb short wave trough comes into a position on the western / southwestern boundary of the most intense moisture and heat flux (**FIG 13**). Since this moist region is now conditionally unstable, the effects of the upward vertical velocities in advance of the 500mb trough is to enhance the upward motion, thus greatly increasing the convective activity in the region. As the individual cells develop, the upper level diffluence present as a result of the upper level long wave trough provides the mass divergence necessary for convection to continue and intensify. As more and more cells develop, they begin to organize (as described by Smull & Augustine, 1993) and develop into a distinct mesoscale system.

The convective elements within the new system are all producing individual meso - highs beneath them as the cold downflowing air within the storm reaches the ground and spreads out. As these cells organize, their cold air outflows combine into a large meso - high cold dome moving outward beneath the system. Another effect of the convective cells is their initiation of gravity waves (Stensrud and Fritsch, 1993) which also propagate outward from the system near the top of the convective elements. These two events are thought to represent the driving forces behind the longevity of nocturnal MCC's (Stensrud & Fritsch, 1993). On the southern flank of the MCC, the low level moisture flow continues from the low level jet. As the upper level gravity waves (which get their energy from the Latent Heat of Condensation released within the convective cells - known as Convective Instability of the Second Kind (CISK)) move outward, the upward vertical motion ahead of the waves initiates new convection. Then, as the low level cold air dome flows into this newly destabilized region, it provides the additional lift required for the convection to continue. The individual cells thus tend to move with the 700mb ambient flow, but since new cells are developing as the old cells move away and weaken, the system is able to maintain its shape and intensity

for long periods (**FIG 14a,b**). The only time MCC's deviate from this 700mb steering flow is in a weakly forced synoptic pattern where the southern flank new cell development is of the same magnitude as the upper level advection. In this case the MCC tends to follow a more southeasterly direction due to the combined effects of eastward steering flow and southward new cell development (Stensrud and Fritsch, 1993). In general, the motion of the circular cloud shield on satellite photography is based on a balance between the strength of the 700mb steering flow and the rate of new cell development in the inflow region. This balance also directly contributes to the classification of the MCC as: 1) a high wind event of 2) a heavy rain event. In the high wind type of MCC, the steering flow tends to be greater than the low level inflow / new cell development so it tends to propagate quickly with the steering flow. This translates to a shorter time in any one location as well as a faster motion over the ground leading to less precipitation and greater wind speeds in any one area. Conversely, the heavy rain MCC's have low level inflow / new cell development of the same order of magnitude as the 700mb steering flow, allowing the system to remain over one particular area for a long period of time. This allows the MCC to drop a large amount of precipitation in a small area due to its slow translation speed over the ground (Ray, 1986).

This whole process continues for several hours overnight .and into the early morning hours. Eventually however, the phase relationship between the low - middle - upper level features begins to breakdown. This breakdown is due to the differences in translation speeds between the different vertical features. At this point, the MCC begins to move into an area less favorable to convective development. In essence, the upper level support (500mb short wave) and the low level outflow boundary move out of the area of maximum low level moisture advection (**FIG 15**). The area of positive vertical velocity enters an increasingly stable airmass, thus shutting off the ability of the MCC to sustain itself. During this phase, the MCC transforms from a convection oriented rain event to a more stratiform oriented rain event (**FIG 16**). By mid - morning the mesoscale structure is destroyed and the last of the systems precipitation falls out, leaving scattered clouds and cooler temperatures in its wake (Johnson & Bartles, 1992).

IV. Summary & Conclusions

The purpose of this paper was to define and describe the key elements necessary for MCC development. How all these elements combine was described in Section III. Most importantly however, the significance of the low level jet on MCC initiation and development was discussed. Through research, several conclusions were developed about the role of the low level jet in MCC development:

1) Without the heat and moisture flux provided by the nocturnal low level jet, suitable atmospheric conditions for sustained MCC activity could not be achieved.

2) The diurnal oscillation of the low level jet directly contributes to the nocturnal nature of both MCC development and the Great Plains convective precipitation maxima.

3) The seasonal variations in the occurrence of the low level jet also correlates directly with the seasonal preference for MCC development.

4) The large scale synoptic events are vital in developing a sufficiently strong low level jet for sustained MCC development.

5) The Bottom Line - the presence of a strong and sustained nocturnal low level jet (with its associated heat and moisture flux) is a necessary condition for MCC initiation and development!

V. Areas Deserving Future Research

While much has been done to improve our knowledge of low level jets and MCC's, there exists several areas where future study would be beneficial:

1) A more thorough understanding of why some convective cells organize into mesoscale systems and why others do not.

2) Better detection methods for low level jets over the Great Plains area of North America.

3) A better understanding of the phase relationship between convection induced gravity waves (sustained by CISK) and new cell development.

4) A better understanding of the phase relationship between convection induced gravity waves and cold air outflow induced new cell development.

5) Investigate the unique radiative relationship between the Cirrus outflow layer and the MCC life cycle.

6) Finally, and perhaps most importantly, improvements in the forecasting techniques used in the prediction of MCC development and movement must be made.

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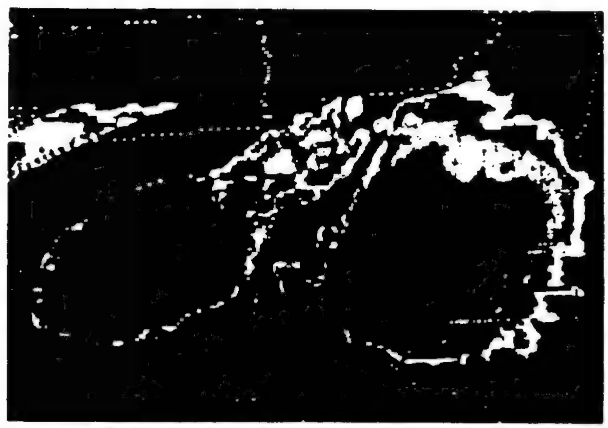
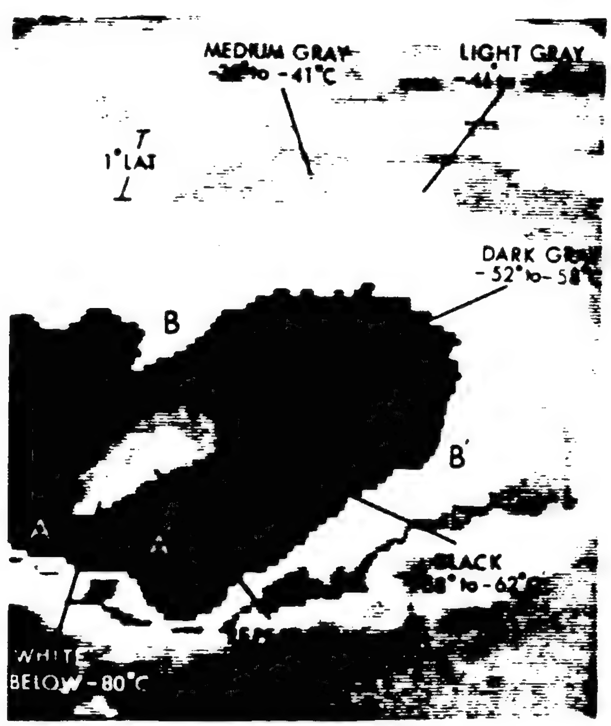
FIGURE #1

(RAY, 1986)



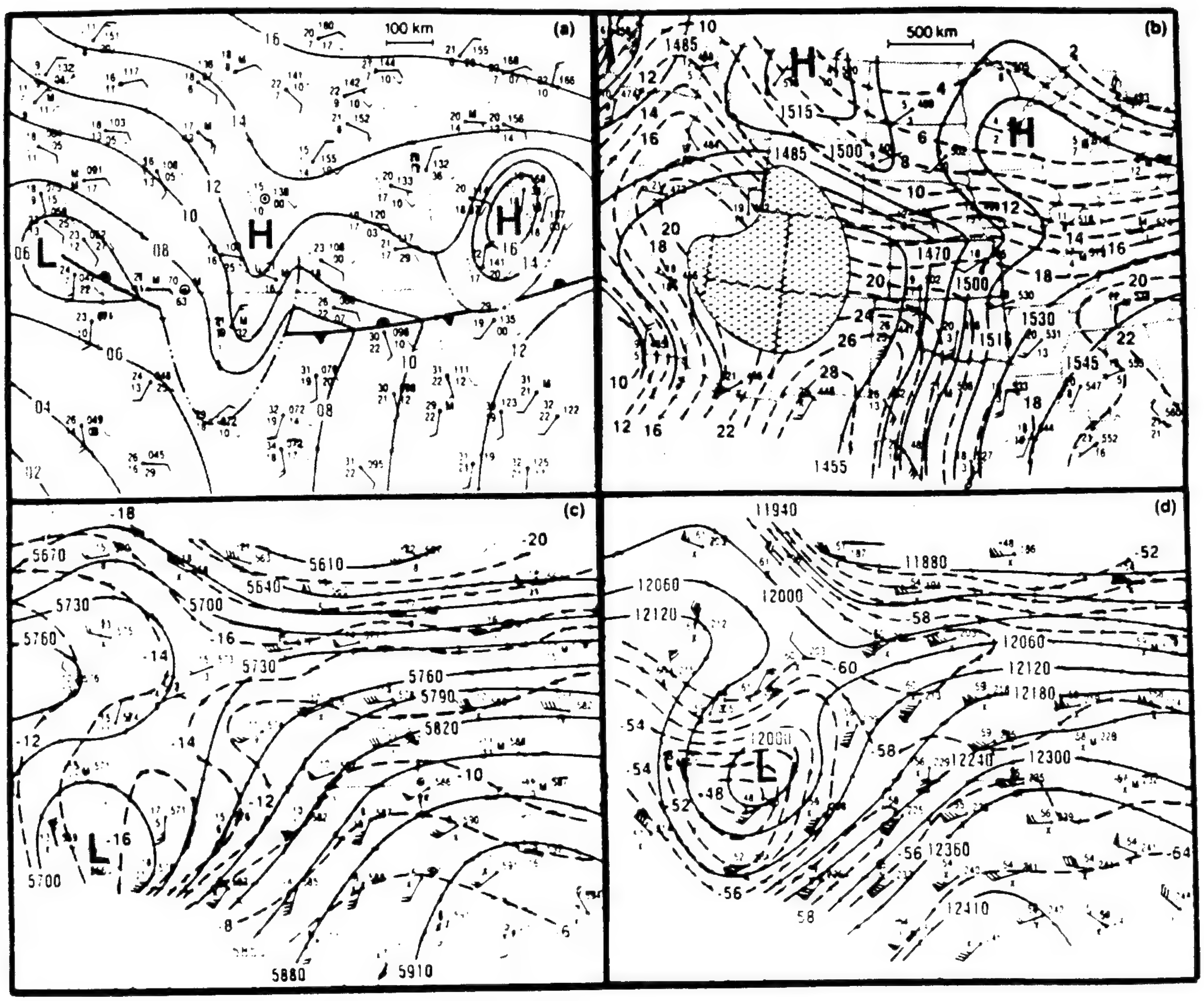
Enhanced infrared satellite image for 0630 GMT 20 May 1979. Black, gray, and white contours indicate increasingly lower infrared temperatures



Infrared image showing the MB enhancement curve temperature ranges that correspond to the various shades of black, gray, and white. (Courtesy of Dr. R. Scofield, NOAA-NESS.)

FIGURE #2

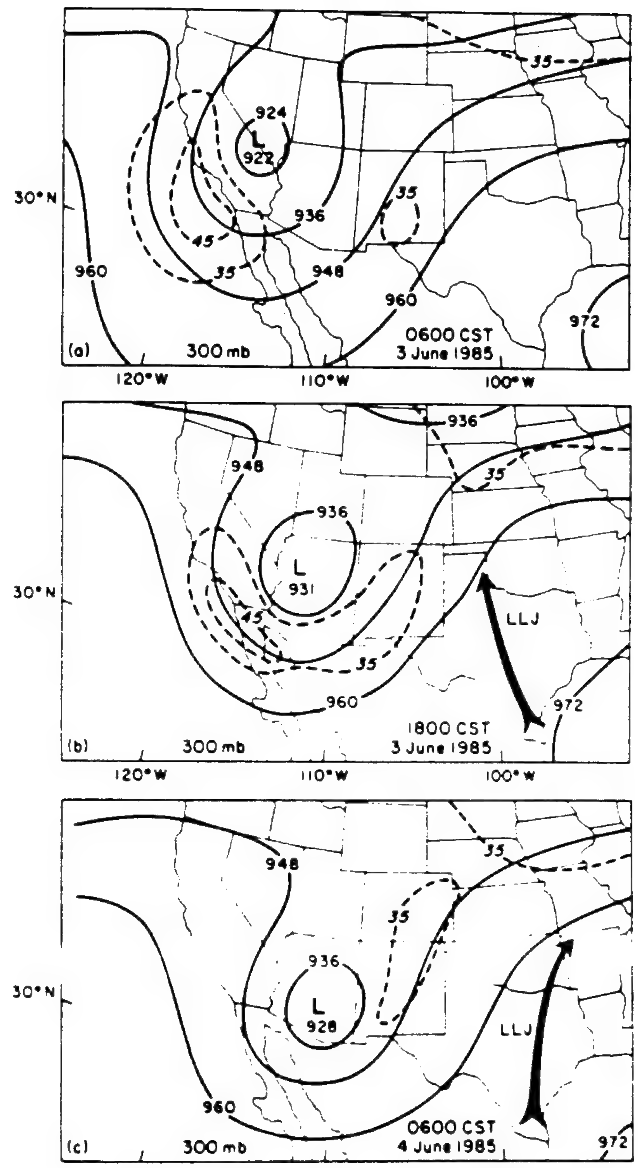
(SMULL AND AUGUSTINE, 1993)



Synoptic-scale analyses at 0000 UTC 4 June 1985 at (a) surface, (b) 850 mb, (c) 500 mb, and (d) 200 mb. Isotherms (°C) are dashed in (b)-(d); solid contours represent mean sea level pressure (mb, leading "10" omitted) in (a), geopotential height (m MSL) in (b)-(d). Horizontal scale in (b) applies to (b)-(d).

FIGURE #3

(TRIER AND PARSONS, 1993)

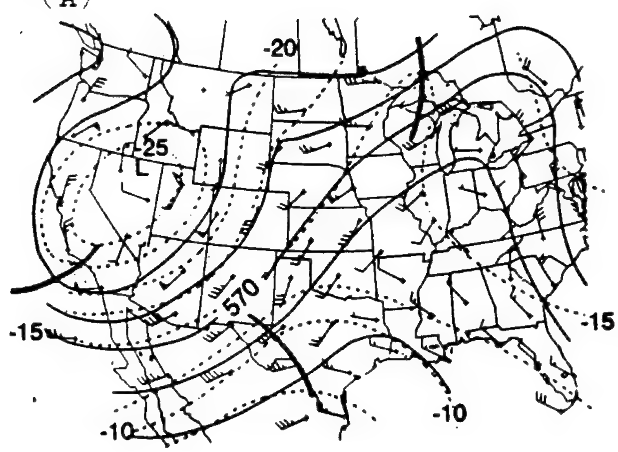


300-mb analysis with geopotential height contours (solid) analyzed in 12-dam intervals with the 35 and 45 m s⁻¹ isotachs (dashed) at (a) 0600 CST 3 June, (b) 1800 CST 3 June, and (c) 0600 CST 4 June 1985. The bold arrow schematically illustrates the approximate streamline of the low-level jet in (b) and (c).

FIGURE #4

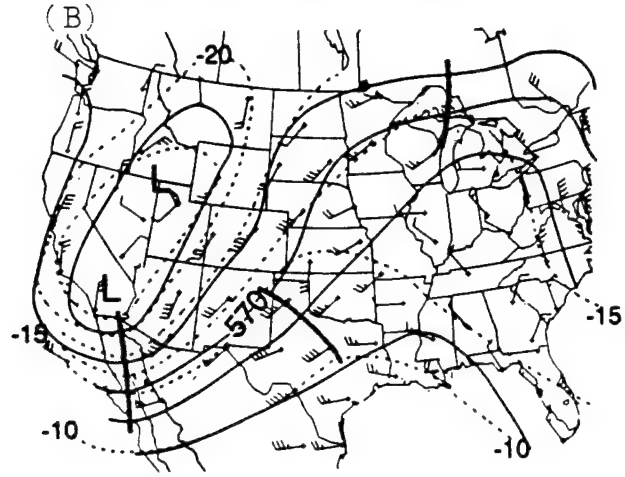
(STENSRUD AND FRITSCH, 1993)

(A)



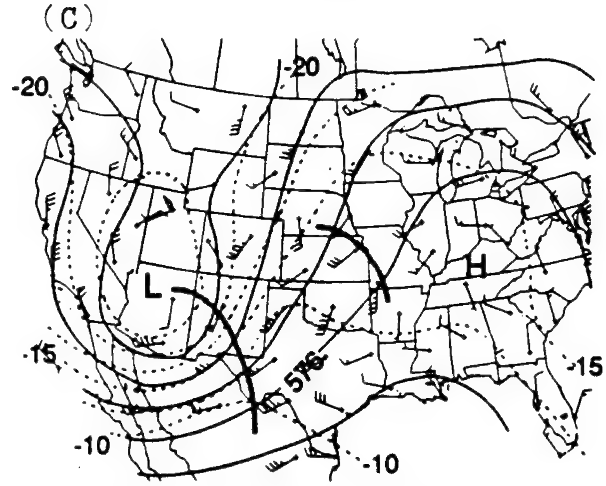
Upper-air analyses at 1200 UTC 11 May

(B)



Upper-air analyses at 0000 UTC 12 May

(C)



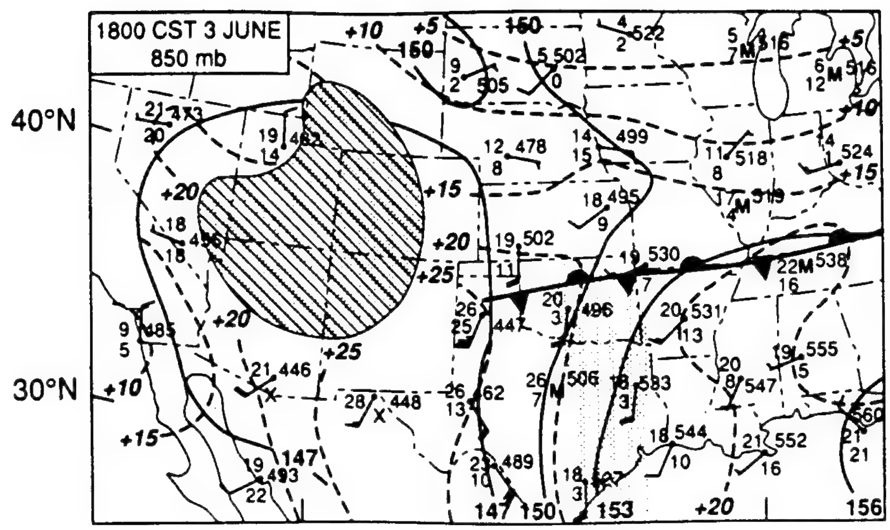
Upper-air analyses at 1200 UTC 12 May

FIGURE #5

(A) (TRIER AND PARSONS, 1993)

(B) (STENSRUD AND FRITSCH, 1993)

(A)



(B)

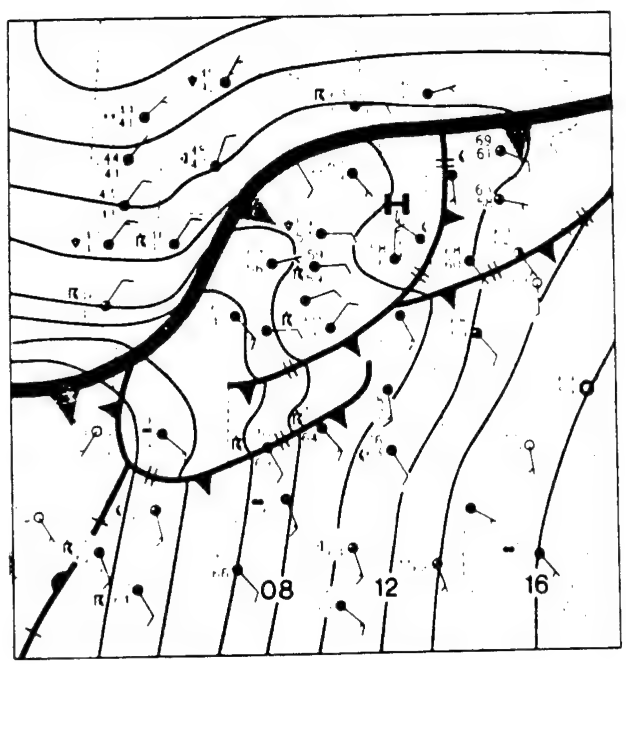
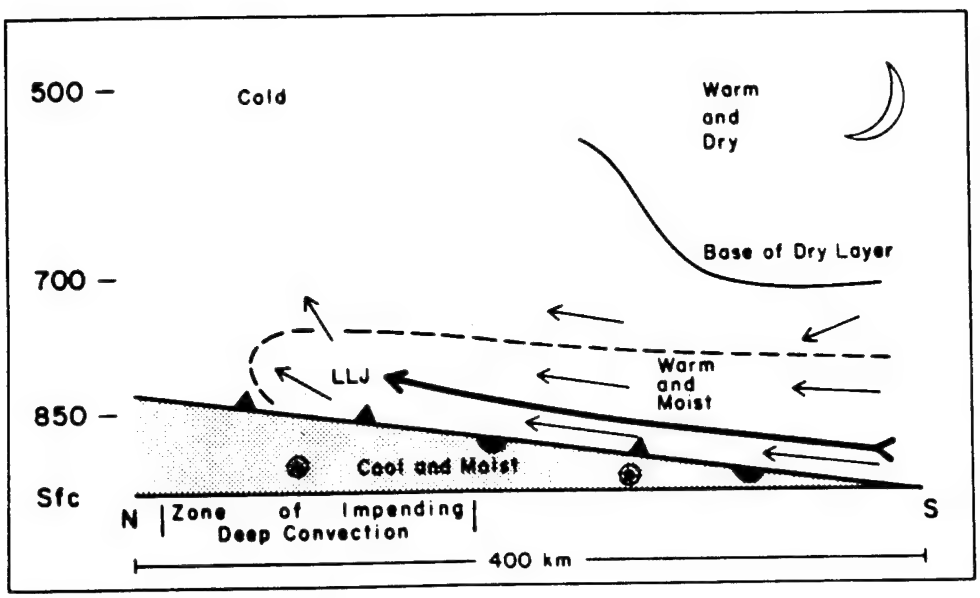


FIGURE #6

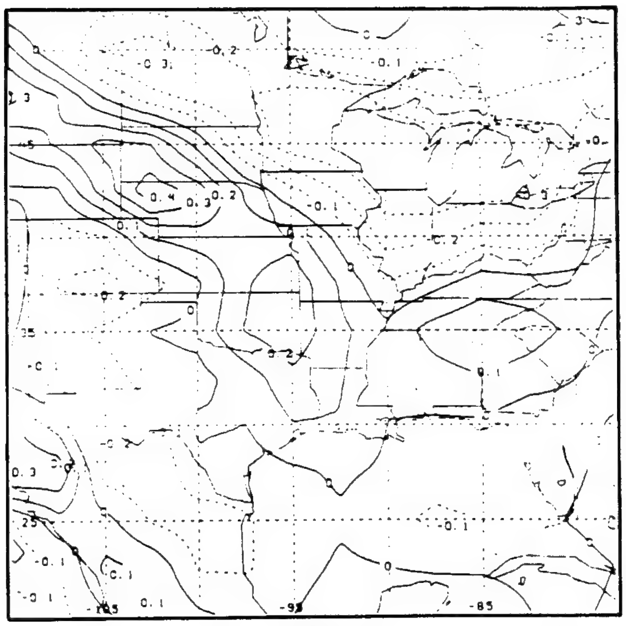
(TRIER AND PARSONS, 1993)



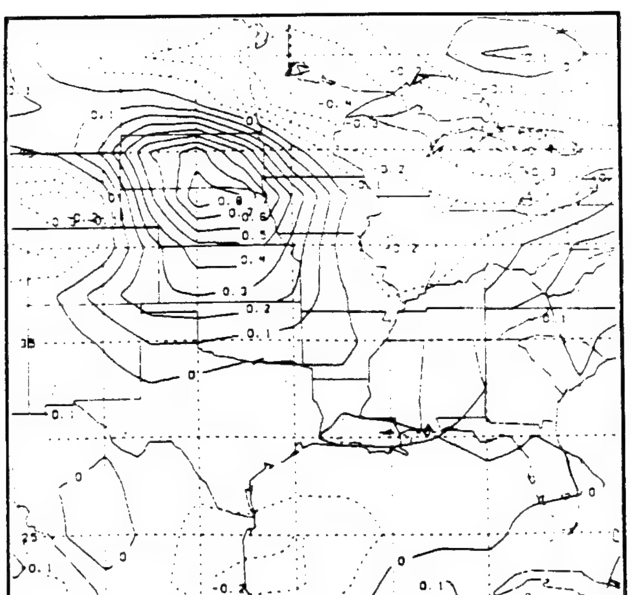
An idealized north–south schematic cross section depicting the thermodynamic and flow structure immediately prior to the development of deep convection above the wedge-shaped cold air mass (lightly shaded). The vectors represent the flow in the x–z plane (vertical component is greatly exaggerated). The dot inside the circle represents easterly flow (out of the page) within the cool, moist air mass below the frontal surface. The dashed line represents the boundary of the warm, moist air mass transported northward above the frontal surface by the southerly low-level jet (LLJ) whose axis is denoted by the bold streamline.

FIGURE #7

(NICOLINI ET AL, 1993)



(a)

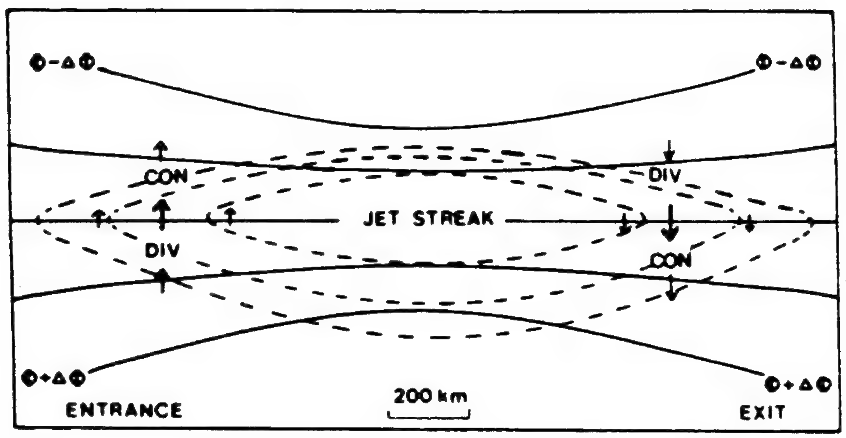


(b)

(a) ECMWF vertical velocity analysis at 500 mb for 0000 UTC 27 May 1984. Contour interval is 0.1 cm s^{-1}. (b) As in (a) at 1200 UTC 27 May 1984.

FIGURE #8

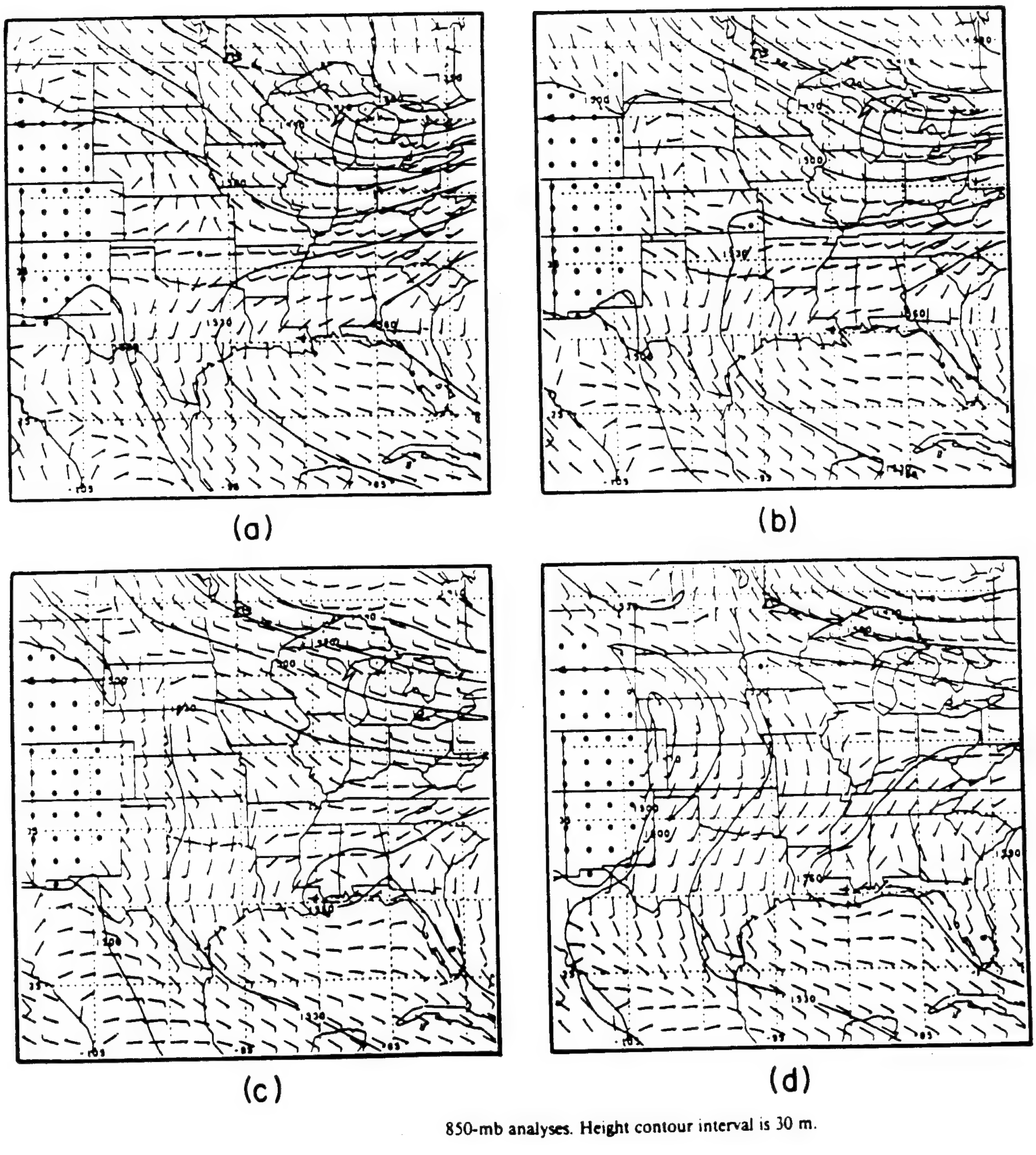
(RAY, 1986)



The ageostrophic motions (arrows) and associated convergence (CON) and divergence (DIV) patterns in the vicinity of a straight jet streak. (From Shapiro and Kennedy, 1981.)

FIGURE #9

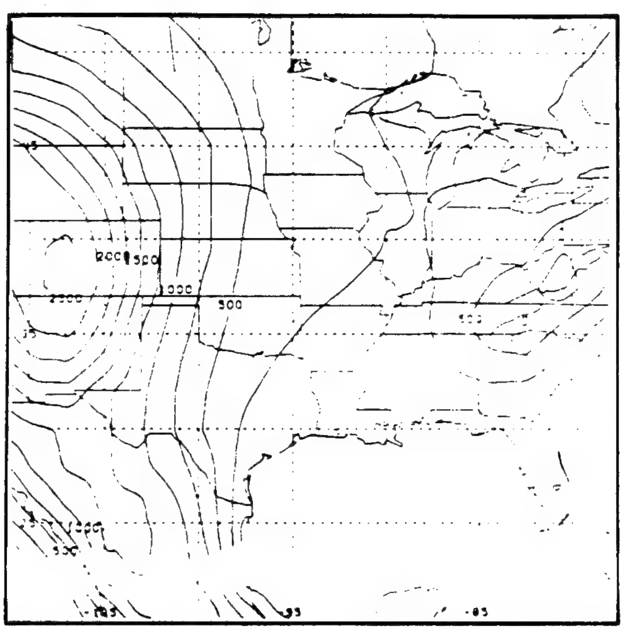
(NICOLINI ET AL, 1993)



850-mb analyses. Height contour interval is 30 m.

FIGURE #10

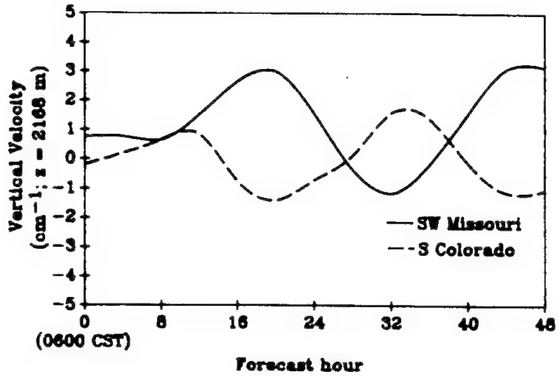
(NICOLINI ET AL, 1993)



Topography used for model integrations.

FIGURE #11

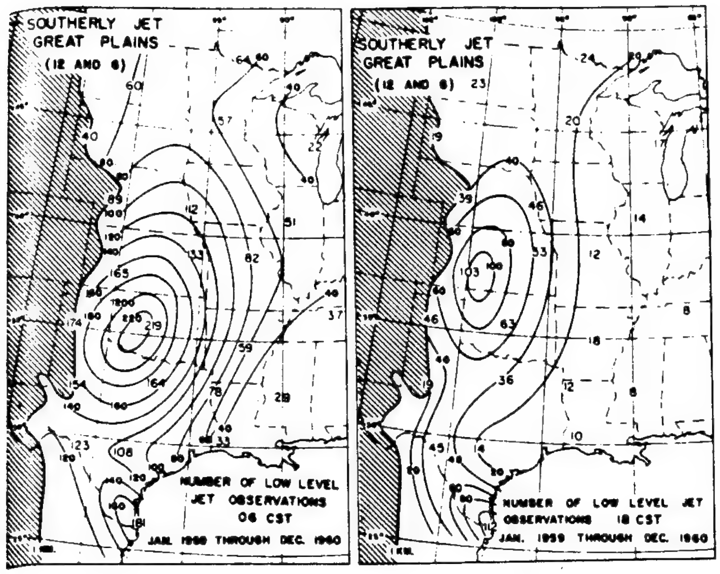
(A)



(McCORCLE, 1988)

Vertical velocity forecast (cm s^{-1}) at 2168 m for grid points in southwest Missouri (solid) and southern Colorado (dashed) for the dry soil case.

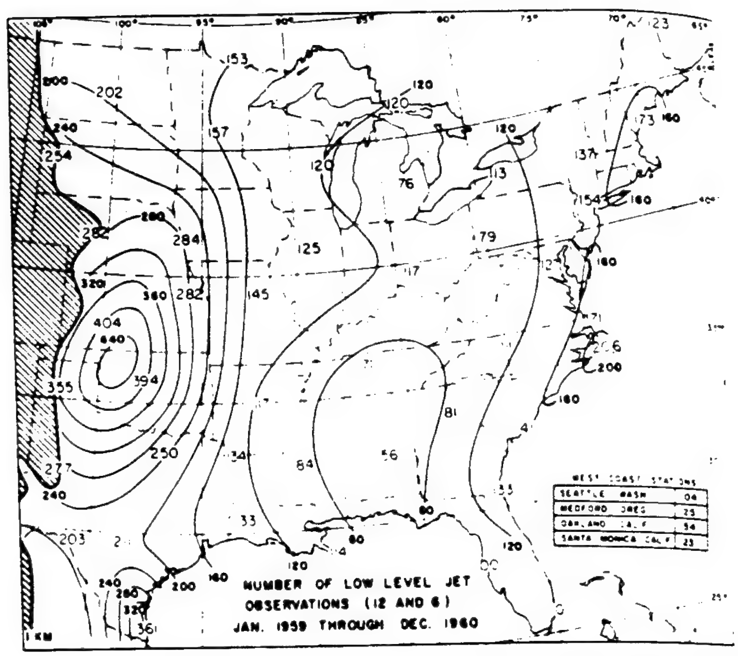
(B)



(BONNER, 1968)

Numbers of Criterion 1 "southerly jet" observations at 06 CST (left) and 18 CST (right). Two years of data.

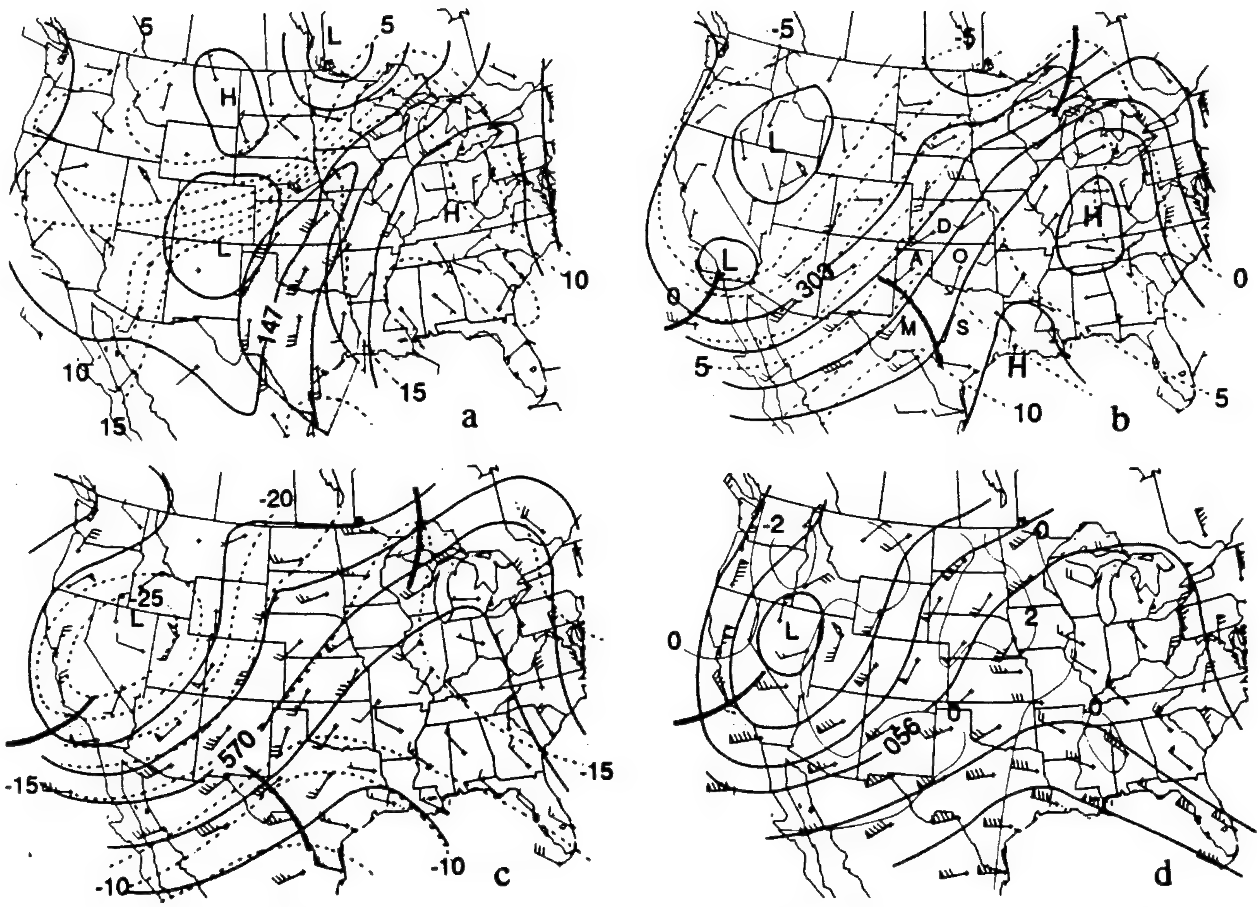
(C)



Number of Criterion 1 low level jet observations from January 1959 through December 1960. 18 CST and 06 CST combined.

FIGURE #12

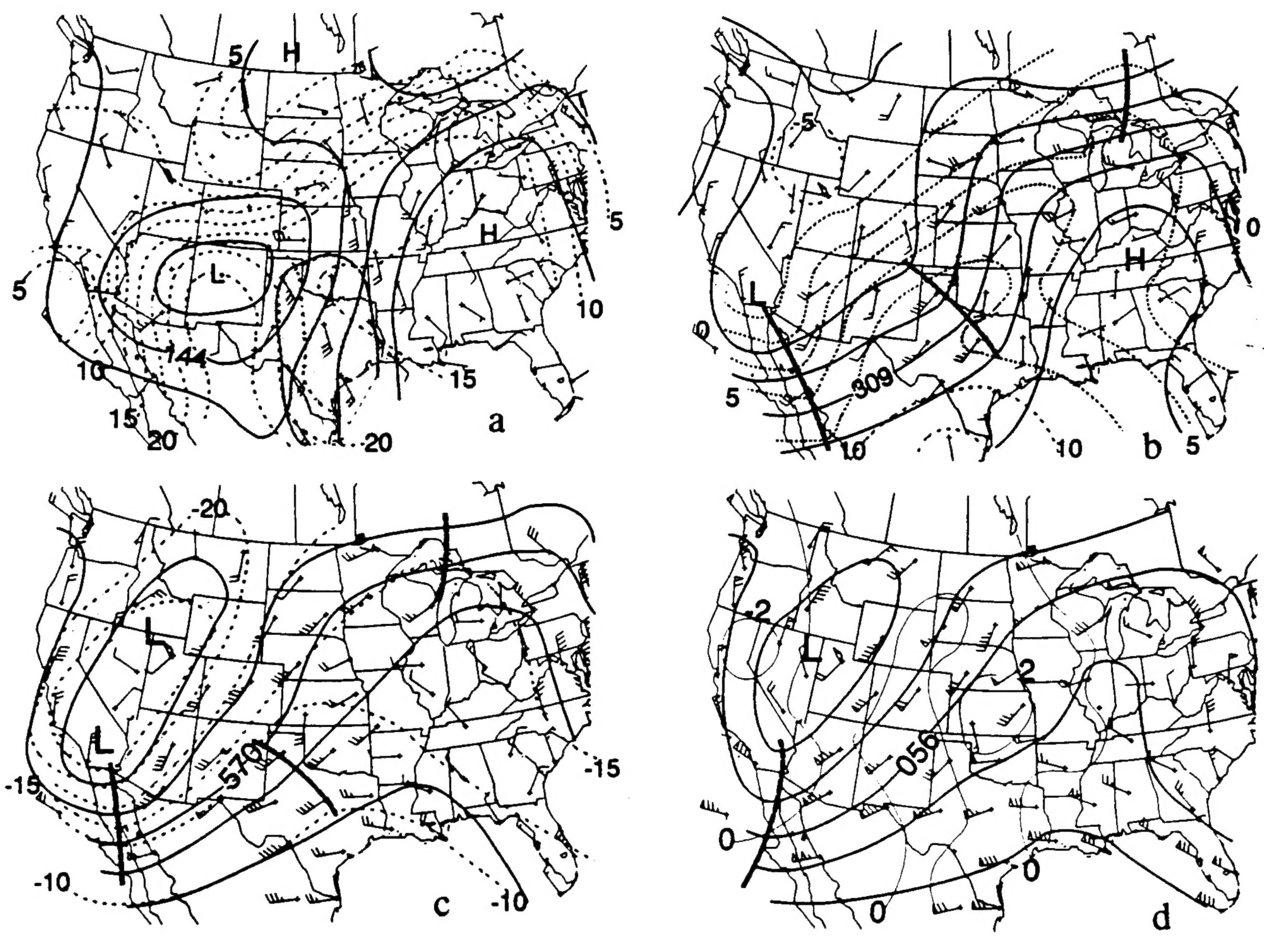
(STENSRUD AND FRITSCH, 1993)



Upper-air analyses at 1200 UTC 11 May for (a) 850 mb, (b) 700 mb, (c) 500 mb, and (d) 250 mb. Winds are in knots (full barb equals 10 kt). Solid lines denote geopotential height contours, dotted lines denote temperature contours (°C), and thick dashed lines denote short-wave positions. Stippled region in (a) denotes mixing ratios greater than 10 g kg^{-1}. In (b), letters *A*, *D*, *M*, *O*, and *S* indicate locations of Amarillo, Dodge City, Midland, Oklahoma City, and Stephenville. Thin solid line in (d) denotes divergence contours in units of 10^{-5} s^{-1}. Height contours at 30-m intervals at 850 and 700 mb, 60 m at 500 mb, and 120 m at 250 mb.

FIGURE #13

(STENSRUD AND FRITSCH, 1993)

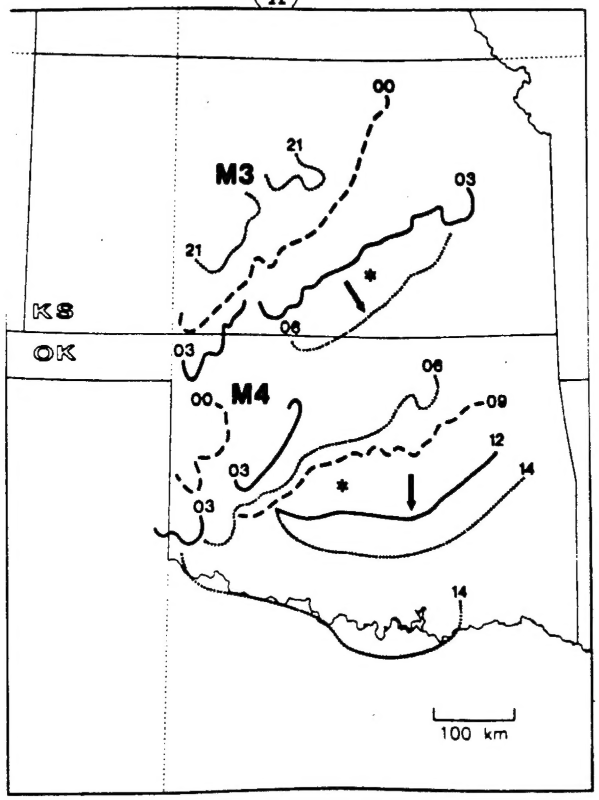


Upper-air analyses at 0000 UTC 12 May for (a) 850 mb, (b) 700 mb, (c) 500 mb, and (d) 250 mb. Winds are in knots. Solid lines denote geopotential height contours, dotted lines denote temperature contours (°C), and thick dashed lines denote short-wave positions. Stippled region in (a) denotes mixing ratios greater than 10 g kg^{-1}. Thin solid line in (d) denotes divergence contours in units of 10^{-5} s^{-1}. Height contours at 30-m intervals at 850 and 700 mb, 60 m at 500 mb, and 120 m at 250 mb.

FIGURE #14

(STENSRUD AND FRITSCH, 1993)

(A)



Isochrones of the leading edge of echoes as observed from the Wichita, Kansas, and Oklahoma City, Oklahoma, radars (locations denoted by asterisks) at approximately 3-h intervals beginning 2100 UTC 11 May 1982 (denoted by 21) and ending 1400 UTC 12 May 1982 (denoted by 14). Analysis based upon examination of actual radar film from these two radars.

(B)

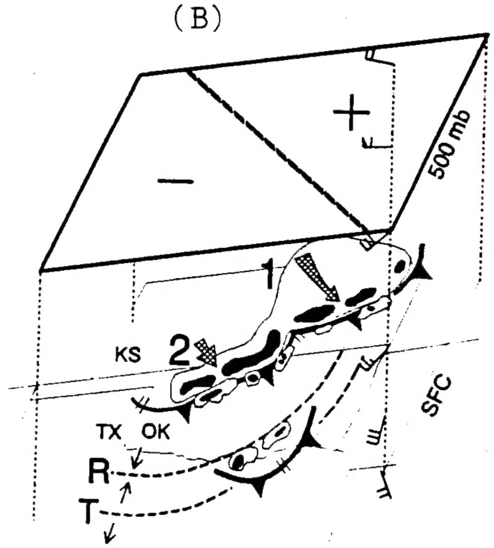
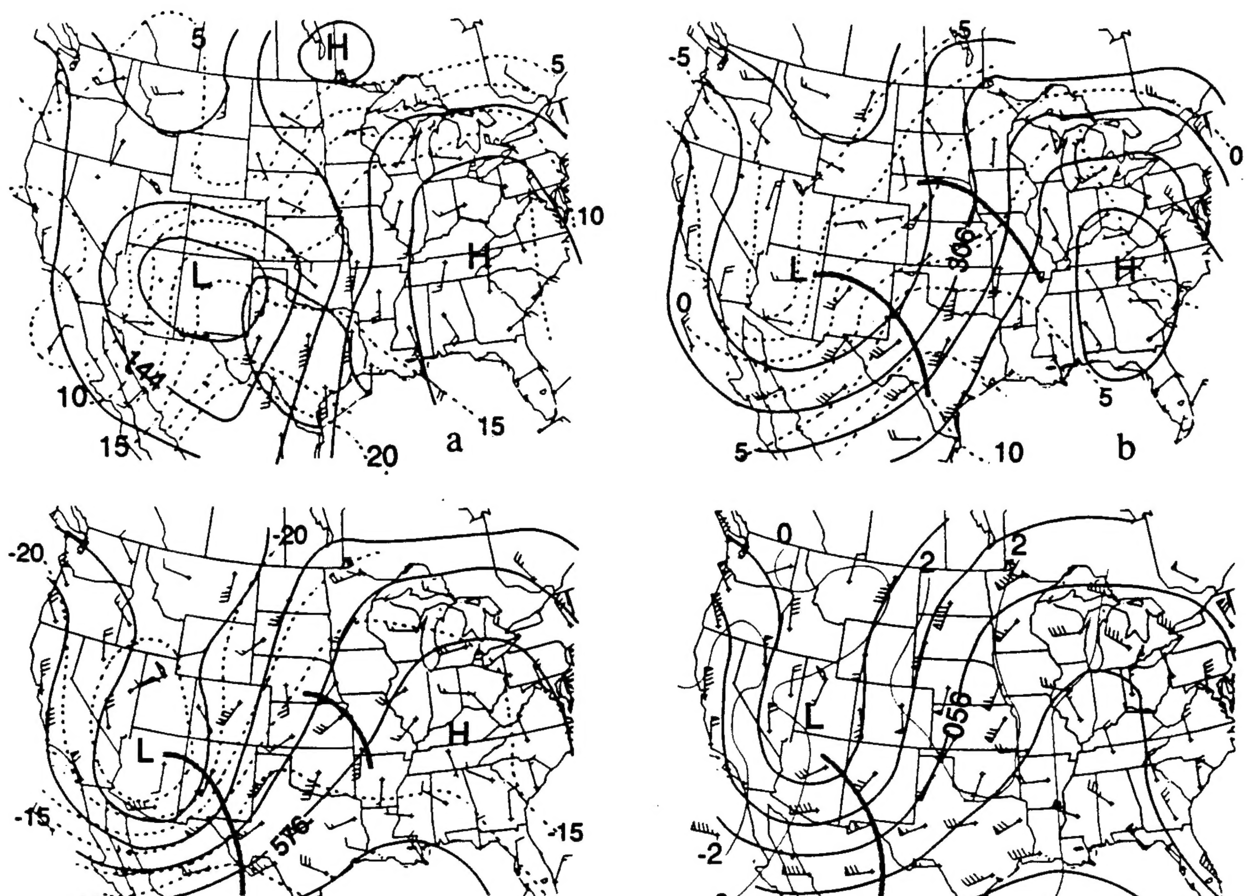


FIGURE #15

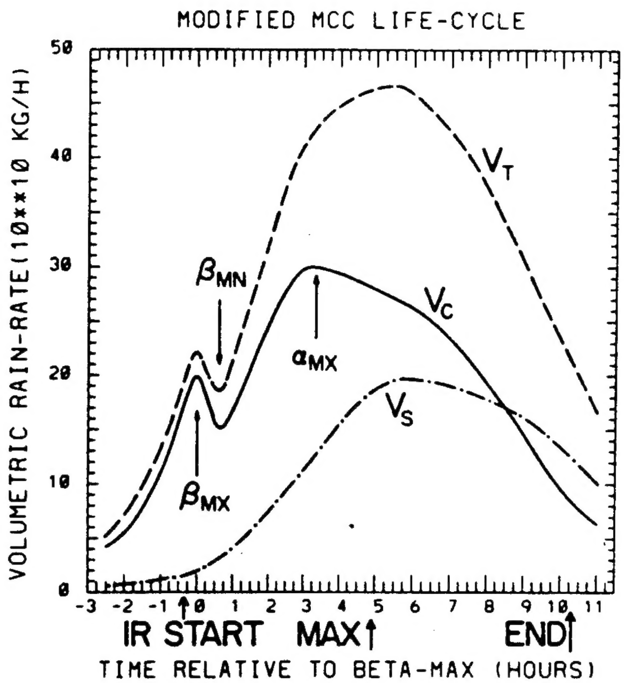
(STENSRUD AND FRITSCH, 1993)



Upper-air analyses at 1200 UTC 12 May for (a) 850 mb, (b) 700 mb, (c) 500 mb, and (d) 250 mb. Winds are in knots. Solid · denote geopotential height contours, dotted lines denote temperature contours (°C), and thick dashed lines denote short-wave positions. led region in (a) denotes mixing ratios greater than 10 g kg^{-1}. Thin solid line in (d) denotes divergence contours in units of 10^{-5} s^{-1}. · contours at 30-m intervals at 850 and 700 mb, 60 m at 500 mb, and 120 m at 250 mb.

FIGURE #16

(McANELLY AND COTTON, 1992)



Modified MCC precipitation life cycle, in terms of volumetric rain rate due to convective, stratiform, and total echo. The growth stage through the α-scale maximum in V_C is based on Fig. 14a and includes the early β-scale convective cycle. The remaining life cycle is adapted from subperiods 6–12 in Fig. 1b, with V_C and V_S based on averages of the two estimates shown there. Slight adjustments are made to the values from Figs. 14a and 1b to ensure a smooth merger at the α-scale maximum in V_C.